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Forest-fire-scar aging using SPOT-VEGETATION for Canadian ecoregions

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Abstract: The mapping of Canadian fires is a large effort supported by provincial, territorial, and federal agencies. Remote sensing techniques can aid in mapping, especially in remote areas and during busy fire seasons. The SPOT-VEGETATION (SPOT-VGT) sensor has previously shown promise at distinguishing fire scars on the landscape. The usefulness of SPOT-VGT to age fires in 18 Canadian ecoregions was evaluated for a period up to 50 years since fire, analysing more than 250 000 pixels (nominal resolution about 1 km^2). The SPOT-VGT reflectances were evaluated using the ratio of the short-wave infrared band (1.58–1.75 μm) to near-infrared band (0.78–0.89 μm), compared with the Canadian large-fire database (fires greater than 200 ha in size). Nonlinear regressions were significant for all ecoregions with r^2 values being greater than 0.57 for 16 of them. Five ecoregions groupings had similar relationships, consistent with their contiguous pattern on the landscape. The prediction of fire-scar age depends on ecoregion and can be successful over periods as short as 6 years to as long as 30 years. The root mean square error for all ecoregions ranged from 5 years for recent burns to about 12 years for three decades following fire. This tool is useful to get approximate fire-scar ages, but the accuracy is limited because of the variation in forest succession on the landscape, and it cannot replace more detailed mapping done currently by fire agencies.

Résumé : Au Canada, la cartographie des feux de forêt requiert un effort important et est supportée par des organismes provinciaux, territoriaux et fédéraux. La télédétection peut faciliter la cartographie, particulièrement dans les régions éloignées et pendant la période où les feux sont actifs. Le capteur SPOT-VEGETATION (SPOT-VGT) s'est déjà avéré prometteur pour distinguer les zones brûlées dans le paysage. L'utilité du SPOT-VGT pour déterminer l'âge des feux dans 18 écorégions du Canada a été évaluée pour des feux vieux d'au plus 50 ans en analysant plus de 250 000 pixels (résolution maximale d'environ 1 km^2). La réflectance du capteur SPOT-VGT a été évaluée à l'aide du rapport de la bande d'onde courte dans l'infrarouge (1.58–1.75 μm) sur la bande du proche infrarouge (0,78–0.89 μm) comparé à la banque canadienne de données sur les feux de grande dimension (feux dont la dimension couvre plus de 200 ha). Les régressions non linéaires sont significatives pour toutes les écorégions avec des valeurs de r^2 supérieures à 0,57 pour 16 d'entre elles. Cinq regroupements d'écorégions suivent des relations similaires consistantes avec leur configuration contiguë dans le paysage. La prédiction de l'âge des feux dépend de l'écorégion et fonctionne pour des périodes aussi courtes que 6 ans jusqu'à environ 30 ans. Dans toutes les écorégions, l'erreur-type varie de 5 ans pour les brûlis récents à environ 12 ans trois décades après un feu. Cet outil est utile pour obtenir l'âge approximatif des feux mais sa précision est limitée à cause de la variation dans la succession forestière dans le paysage et ne peut remplacer la cartographie plus détaillée qui est couramment faite par les organismes responsables des feux de forêt.

[Traduit par la Rédaction]

Introduction

The magnitude of forest sources and sinks of carbon is an important part of the global carbon balance (Dixon et al. 1994; Goodale et al. 2002). In the boreal forest biome, forest fires are one of the main disturbances that affect the carbon balance, causing large releases of carbon during the combustion process and changes to the rate of carbon sequestration by vegetation in the postfire environment (Amiro et al. 2001; Dixon and Krankina 1993; Kasischke and Stocks 2000). Current and historical databases on the amount of area burned throughout the boreal forest are central to our ability to accurately determine the contribution of fire to carbon dynamics. In particular, historical databases are incomplete in Canada prior to about 1960, although we believe that most of the area burned by large (>200 ha) fires has been correctly estimated since the early 1970s (Stocks et al. 2002).

Currently, Canadian agencies map each fire that burns within their jurisdiction. However, the detail of mapping depends on the agency, the location of the fire, and the resources available. Nationally, fires greater than 200 ha account for most of the burned area, and much of the inventory mapping has focused on these large fires (Stocks et al. 2002). These amount to several hundred large fires each year. Remote sensing techniques, including aerial photography and satellite imagery, are often used to map fires, but fire perimeters can now be easily mapped using a global positioning system mounted on a helicopter. This technique provides great detail but may not be cost-effective for large fires in remote areas, especially if they were not suppressed.

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Hence, there is a need for additional cost-effective mapping tools for large fires to help build national inventories. These tools can also be applied to other countries, where fire mapping is not easily done through conventional methods (e.g., Cahoon et al. 1994). Retrospective mapping also requires the ability to correctly identify the age of fire scars, because models are often run on yearly to 5-year time steps, where the amount of disturbance is a required input (e.g., Kurz and Apps 1999; Chen et al. 2000, 2003).

Previous applications of satellite remote sensing to map burned forested areas have used sensors from the U.S. National Oceanic and Atmospheric Administration (NOAA) advanced very-high resolution radiometer (AVHRR) (e.g., Flannigan and Vonder Haar 1986; Cahoon et al. 1994; Li et al. 1997, 2000; Fraser et al. 2000*a*) and Landsat satellites (e.g., White et al. 1996; Kushla and Ripple 1998; Ahern et al. 2000). The larger pixel size of the AVHRR data (nominally 1 km^2) is suitable for very large fires whereas the small Landsat pixel size (<80 m depending on the sensor) offers much more detail. Although these satellites have been used successfully for fire mapping, newer sensors are being designed to enhance vegetation differentiation. The SPOT-VEGETATION (SPOT-VGT) sensor has shown superior potential to AVHRR for differentiating burned areas with about the same pixel size (Fraser et al. 2000*b*; Fraser and Li 2002). Unlike AVHRR, SPOT-VGT has a shortwave infrared (SWIR) band that is sensitive to changes in vegetation cover. Recently, Fraser and Li (2002) demonstrated that SPOT-VGT was successful at estimating fire-scar age with a root mean square (RMS) error of 7 years for fires in Manitoba and Saskatchewan. In the present paper, we build on this potential and evaluate the use of SPOT-VGT data to identify the age of fire scars across the Canadian boreal forest. This evaluation is possible because of the parallel development of a polygon version of the Canadian large-fire database, which delineates fire boundaries on the landscape. Previous comparisons between this database and remote sensing data have shown good compatibility to evaluate changes in vegetation patterns following fire (Amiro et al. 2000).

Materials and methods

Physical principles

SPOT-VGT has a nominal pixel resolution of about 1 km^2. Of the four spectral bands useful for monitoring vegetation over large areas, the near infrared (NIR) (0.78–0.89 μm) and SWIR (1.58–1.75 μm) bands show the greatest response to vegetation changes following fire (Fraser et al. 2000*b*). The NIR band reflectance decreases immediately after fire, recovering as new vegetation grows because vegetation is highly reflective in this band. Although the SWIR band shows an immediate decrease following fire, in a few days it increases above prefire levels (Fraser et al. 2000*b*). The increased reflectance is caused by less absorption of these wavelengths by the lesser amount of vegetation on the landscape. This has also been observed using Landsat thematic mapping of fires using thematic mapper band 5 (White et al. 1996). Given these two patterns of reflectance changes, the SWIR/NIR ratio will increase following fire, i.e., SWIR increases while NIR decreases. Fraser and Li (2002) confirmed that using a ratio with SPOT-VGT, similar to the concept of the Normalized Difference Vegetation Index (NDVI, Tucker 1979), increased the ability to distinguish time since fire on the landscape. As vegetation increases following fire, the SWIR/NIR ratio will decrease as the SWIR reflectance decreases and the NIR reflectance increases to the prefire state.

Fire polygons from the large-fire database

The polygon version of the large-fire database is an evolving data set. It includes polygons mapped in a geographical information system, which delineates the outline of the fire and attribute information, such as fire start date, year of fire, fire number, and final area burned. Large unburned islands are sometimes delineated. Each agency (provinces, territories, Parks Canada) maintains its own database, with periodic updates as new information becomes available or previously recorded fires are digitized. The national version of this database combines files from all agencies, and it evolves as new information from the agencies becomes available. For the present study, we have used the national database version that was available in December 2001. We included 8880 fire polygons distributed across much of the boreal and taiga ecozones, going back as far as 1945 in some areas. Figure 1 plots polygons of the fires with delineation of ecoregions analysed in the study. More recent versions of this database include additional fires that now have mapped polygons. However, some agencies are electing to not map polygons explicitly for some fires, but instead to represent these fires by a circle of magnitude equal to the final area burned. This technique reduces mapping effort, but does not provide information on fire shape or boundaries.

In addition to the polygon database, there is a point data set of large fires in Canada (Stocks et al. 2002). This data set does not include the delineation of fires geographically, but does include the geographical location of the starting point of the fire as well as other attributes. There are cases where point data are available, but the polygons have not been mapped. This provides an opportunity to use the point data set as identification of a fire that occurred and use a remote-sensing technique for fire scars to delineate a polygon for this fire. We believe that there may still be a small number of fires that are missed in all databases, even in recent years, but these probably represent only a small percentage of the area burned. However, there are some areas in the north where fires have not been mapped, especially prior to about 1980. In general, the quality of data gets better everywhere in more recent years, with many fires potentially missed prior to about 1960.

SPOT-VGT data

Nine 10-day cloud-free Canada-wide composites from 1 June to 30 August 1998 were ordered through Centre National d'Études Spatiales (CNES) of France from the Viaamse Instelling voor Technologisch Onderzoek (VITO) centre in Belgium. A maximum NDVI criterion was used in producing the composites from daily cloudy images. The composites were received as reflectance images after atmospheric corrections. The reflectance data in large ranges of view zenith angle and solar zenith angle were normalized to a common geometry, i.e., nadir view and 45° solar zenith angle (Cihlar et al. 1997), using a modified Roujean model

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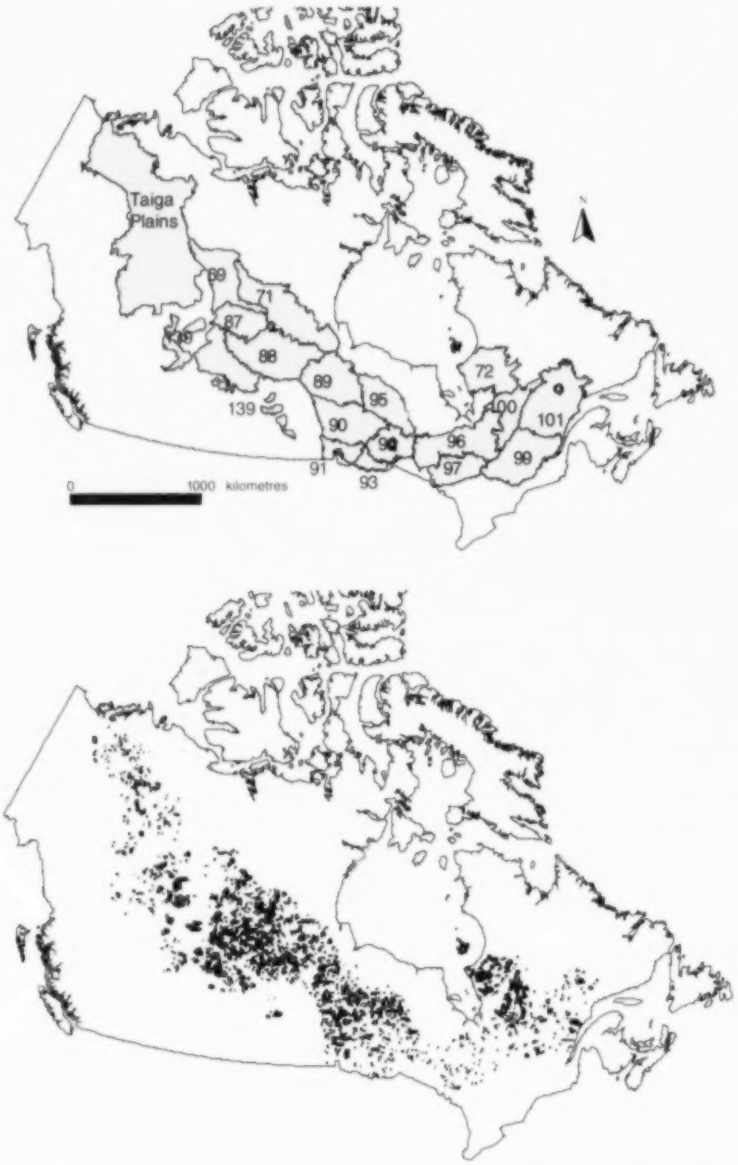
Fig. 1. Location of Canadian ecoregions and fire polygons used in the analyses. Note that the black areas in the fire map are actual fire polygons.



(Roujean et al. 1992; Chen and Cihlar 1997). Ratios of SWIR to NIR in these nine images were averaged for each pixel to produce a single ratio image for the midsummer. This averaging process further reduces remaining noise in the image arising from various sources, including angles of observation and illumination, atmospheric correction, changes in surface wetness due to rainfall events, and uneven phenology. An eight-bit classification was used (i.e., 0–255 ratios of SWIR/NIR), where water was set at 0.

Derivation of fire scar age

The analyses were done within the ArcView GIS (ESRI 1998). For areas that burned more than once over the analysis period, only the most recent fire was used. This eliminated some of the older burned areas that had subsequently reburned. We then created a new file of nonoverlapping fires and defined a subset for each ecoregion. Ecoregion was chosen as the best geographical unit, since it is defined based on relatively homogeneous features in landform, vegetation, and climate. Despite this, vegetation succession trajectories can vary widely within an ecoregion or can be similar among ecoregions because of specific site characteristics. Forest characteristics for each ecoregion are given by Lowe et al. (1996). Eighteen ecoregions or ecoregion groupings were selected based on having a sufficient number of fires for analysis (Fig. 1). All ecoregions within the Taiga Plains ecozone were grouped because of an insufficient number of fires within any given ecoregion in this area. Similarly, ecoregions defined as part of the Midboreal Uplands of the Boreal Plains ecozone were grouped (ecoregions 139–141,

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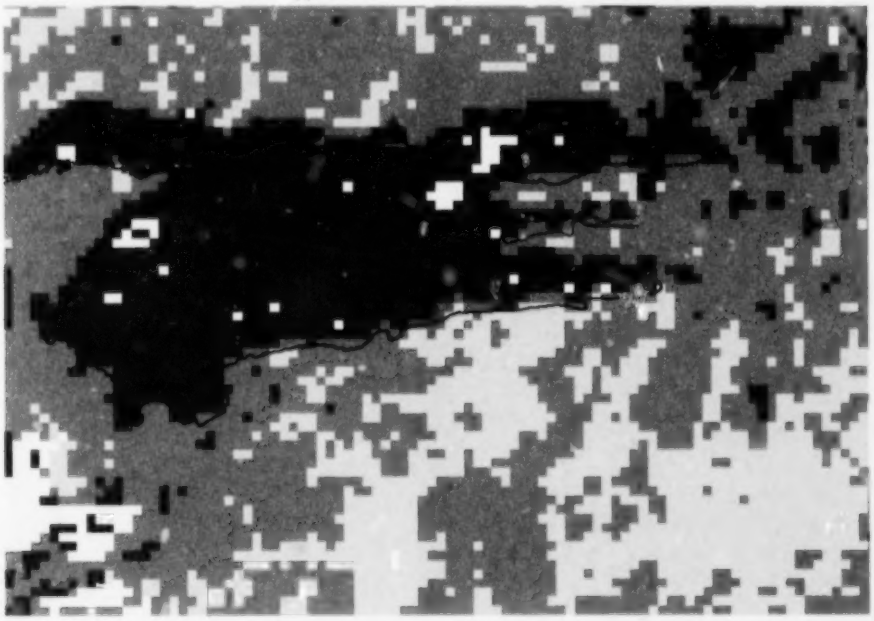
Fig. 2. Example of agreement between SPOT-VEGETATION (SPOT-VGT) mapping and fire polygon from the large-fire database for fire NIP136 (area = 113 000 ha) burned 1995 in ecoregion 95, Ontario. Darker pixels delineate higher reflectance ratio values; white pixels are water. The black outline is the official mapped fire boundary. Pixel size is nominally 1 km^2.



147, 150–154; Lowe et al. 1996). The fire polygons were converted to a grid format coregistered with the SPOT-VGT pixels and a table generated from the SWIR/NIR value (scale of 0–255) and the year of the fire corresponding to this value. This was done by creating a mask to only analyse SPOT-VGT reflectances within a fire polygon. A file of the number of pixels classified for each reflectance class and each year allowed us to generate statistics and histograms for the population of data. Relationships between SWIR/NIR reflectance and time since fire were generated using regression analyses in Sigmaplot (SPSS, Inc. 1998).

Tests of age relationships on the landscape

An independent test of the success of dating fire scars was done using the large-fire point database for fires when we did not have polygons available to develop the fire–age relationships. We selected areas in ecoregions 94 and the Taiga Plains, where five points without polygons were selected in each ecoregion at times since fire of about 3 and 15 years. These points represent the location of the start of the fire, but we could clearly see the fire scar associated with each point for the most recent cases. We then delineated a new fire polygon for this point, ensuring that the area of the polygon approximately matched the final area of the fire reported in the point database. For very large fires, we simplified this by sampling along three north–south transects across the fire. We then compared the SWIR/NIR reflectance characteristics for each polygon with the previously developed regression relationship.

Results

Relationships for ecoregions

Recent fires were easily identified with the SPOT-VGT data and clearly matched the polygon database. Figure 2 is an example of a 1995 fire in ecoregion 95, where the polygon delineation corresponds well with the SPOT-VGT pixels. Older fires were not always obvious. To build the relationships, we analysed over 250 000 pixels for the period ranging from 1946 to 1997. In any given ecoregion and any given year, there was a population of SWIR/NIR reflectances (Fig. 3). The shape of the distributions varied, but was close to Gaussian in many cases. We evaluated the use of different statistical indicators, including the mean, maximum value, and 90th-percentile value. There was no marked advantage of using cut points near the high end of the distribution (e.g., 90th percentile), so we have used the mean SWIR/NIR reflectance value as our fire-age indicator. We developed regressions of mean SWIR/NIR value against fire age for each ecoregion (Fig. 4, Table 1). We selected an exponential functional form of $y = y_0 + a \exp(-bx)$, which allowed for the decreasing slope of the relationship over time. This form was superior to either linear or first-order exponential regressions for most of the ecoregions. It also makes ecological sense because of the expectation that vegetation changes will be most rapid in early years, with smaller changes in overall reflectance in later years, especially following crown closure. However, it does impose an asymptote that needs to be considered for estimates of fire-scar age for a given reflectance. Sixteen of the ecoregions had r^2 values exceeding 0.57. Regressions were statistically significant at $P < 0.01$, except for ecoregions 72 and 101, which were significant at $P = 0.02$. It is clear that the ability to estimate fire-scar age decreases with time since fire. We estimated the period of reasonable predictability based on the derivative of the nonlinear regression, defined as having a limit when the change in the SWIR/NIR value per year is less than one unit. This is an arbitrary value, since a 16-bit classification would give greater resolution. However, it does indicate the approach to the asymptote and forms a definable

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guideline. This ranged from 6 to 30 years, depending on ecoregion (Table 1).

We tested for significant differences among the ecoregion slopes using a general linear model procedure (SPSS, Inc. 1997) based on linear regressions of all combinations of ecoregions. The linear regression simplified the statistical tests and yielded 10 ecoregion groupings where new regressions were calculated. The groupings were ecoregions 69 and 71 ($P = 0.11$); 89, 95, and 96 ($P = 0.30$); 90, 91, 93, and 94 ($P = 0.25$); 97 and 99 ($P = 0.44$); and 72 and 100 ($P = 0.81$). The Taiga Plains and ecoregions 87, 88, 101, and 139 remained as significantly different relationships ($P < 0.05$). The only statistical exceptions were ecoregions 139 and 90, which were not significantly different ($P = 0.21$). However, ecoregion 139 was different from 91, 93, and 94 and was therefore not grouped with these other ecoregions. The P values given here were not adjusted for Bonferroni effects because the tests among ecoregions are largely independent of interactions with the excluded ecoregions (i.e., paired tests are appropriate). These groupings are reasonable ecologically and geographically, since they represent contiguous ecoregions (Fig. 1). Using these ecoregion groupings, we calculated nonlinear regressions as before, with the coefficients presented in Table 1. In general, these groupings did not decrease the r^2 values by very much and, hence, are useful for covering a wider geographical area than a single ecoregion.

A nonlinear regression of all data, irrespective of ecoregion, gives an r^2 value of 0.32. It is possible to normalize the data based on ecoregion to improve this regression, but this prevents the use of the equation for prediction because some a priori knowledge is necessary. We attempted some normalization methods based on neighbouring pixels of mature forest, defined as those having small SWIR/NIR values. However, these were not particularly successful and require substantial further investigation to derive reliable normalization methods.

Algorithm tests

The ecoregion-specific algorithms were tested on 20 fires in two ecoregions for two time periods. None of these fires had been used in the original regression analysis because polygons were not available at that time. For recent fires in the mid-1990s, our regression equations estimated a fire-scar age that was within 3 ± 1.0 (mean ± 1 SD, $n = 5$) years of the actual fire age for ecoregion 94 and 4 ± 3.6 ($n = 5$) years for the Taiga Plains. Estimations of fire age for ecoregion 94 are very unreliable past 11 years following fire as the asymptote is approached. For three fires in the early 1980s, the reflectance was below the asymptote and could not be aged. For two fires in the late 1980s, the regression predicted the fire age to be 5 years older than actual. In the Taiga Plains, fires from the early 1980s were aged as a mean difference of 6 ± 6.5 ($n = 5$) years from actual. However, three of these fires were within 2 years of the correct fire year.

Discussion

The SPOT-VGT reflectance data differentiate amounts of biomass following a fire. The rate of vegetation recovery depends on burn severity, climate, soil, vegetation type, and seed sources. In general, we would expect a curvilinear relationship with more rapid increase in biomass during the first decade or so, with a slower change once the forest canopy becomes closed. This type of relationship is evident in Fig. 4, especially for the southern boreal shield areas, such as ecoregions 90, 91, 93, 94, 96, 97, and 99. Severe fires in these shield areas also cause erosion, and the amount of bare rock may be an important factor in the remotely sensed signal.

Many of the northern ecoregions have a more linear relationship, likely because of a slower successional response to fire. For example, the change in reflectance of open lichen woodlands may contribute the strongest signal, and the rate of replacement of lichens may follow close to a linear trend. All reflectance changes over time depend on the postfire successional trajectory. Further south in the Midboreal Uplands (ecoregion 139 in Fig. 1), the successional pattern following fire usually involves the rapid establishment of some vegetation cover, often aspen (*Populus tremuloides* Michx.) growing from suckers, immediately following a fire. It is likely that the steady change in the reflectance ratio is

Fig. 3. Distribution of shortwave infrared/near infrared (SWIR/NIR) ratio values for 1994 and 1984 fires for Ecoregion 87 in Saskatchewan.

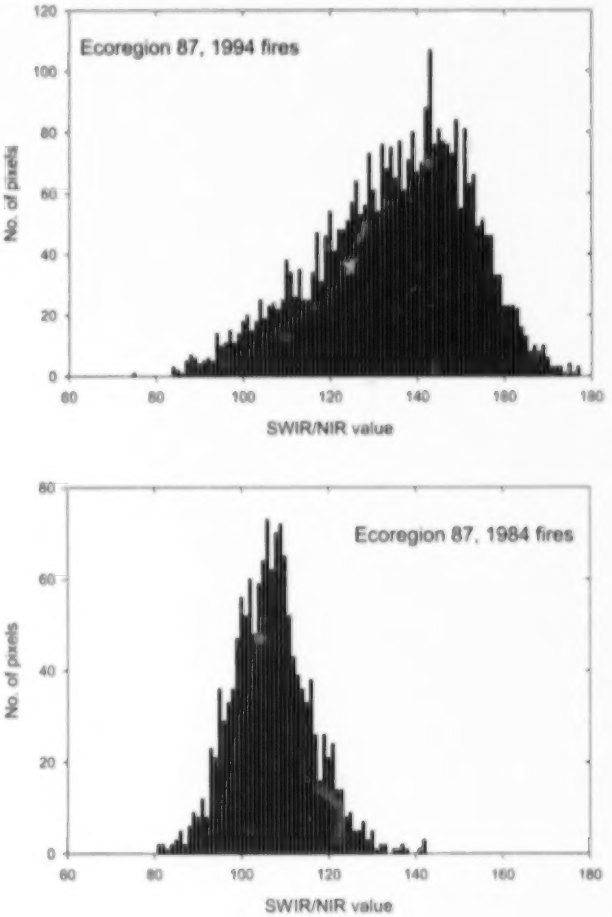

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Fig. 4. Nonlinear regressions of shortwave infrared/near infrared (SWIR/NIR) ratio with time since fire (years) for 18 ecoregions (mean ± 1 SE). Coefficients are given in Table 1.

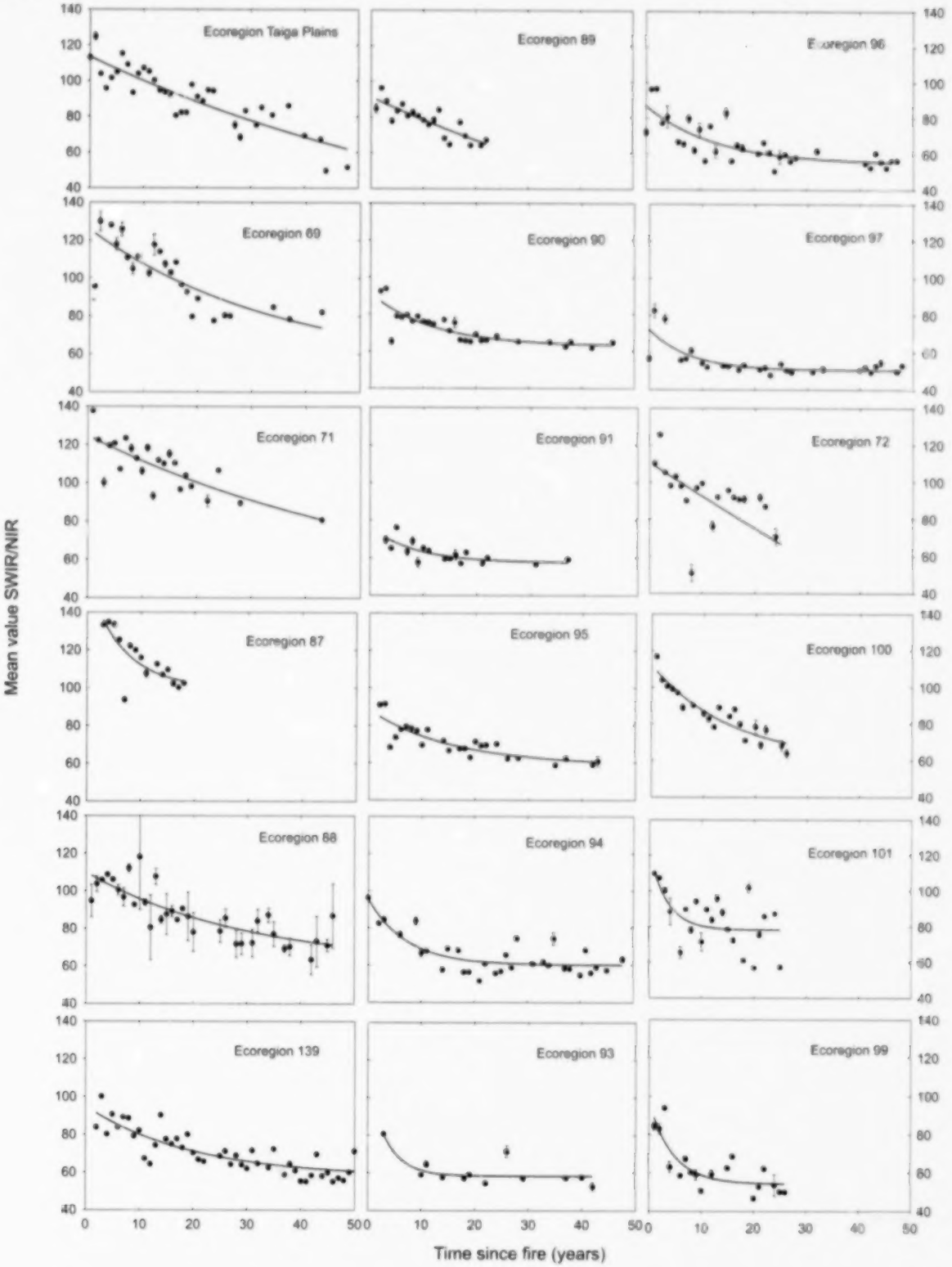

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Table 1. Regression equations for each ecoregion (and combinations of ecoregions), as $y = y_o + a \exp(-bx)$, where y is the mean SWIR/NIR ratio calculated for a given fire scar age x (years).

Ecoregion	y_o	a	b	Period since fire analysed (years)	Number of pixels	r^2	Period of reasonable prediction (years)
100	60	52.3	0.065	20	8 257	0.87	18
101	78	44.6	0.295	22	10 092	0.35	8
139	58	37.4	0.051	46	30 285	0.68	12
69	53	72.9	0.029	24	6 867	0.66	24
71	40	84.4	0.017	23	19 868	0.60	20
72	–344	454.2	0.0041	20	22 504	0.36	20
87	100	57.4	0.154	15	20 045	0.63	14
88	61	48.9	0.034	34	30 949	0.66	15
89	–25	115.9	0.0116	20	15 877	0.72	20
90	63	28.6	0.085	27	26 934	0.69	9
91	57	19.0	0.118	17	2 248	0.58	6
93	58	52.2	0.281	12	659	0.65	9
94	60	35.6	0.140	30	3 498	0.68	11
95	59	29.7	0.065	25	10 101	0.73	9
96	54	32.4	0.078	32	3 830	0.62	12
97	50	22.0	0.131	26	2 151	0.58	8
99	54	43.6	0.220	18	2 766	0.68	9
Taiga Plains	–135	246.8	0.0047	34	39 055	0.77	30
Combinations							
69, 71	47	78.4	0.023			0.63	
89, 95, 96	55	36.8	0.067			0.69	
90, 91, 93, 94	61	30.6	0.136			0.48	
97, 99	51	30.2	0.130			0.59	
72, 100	67	44.6	0.0812			0.32	

caused by a continuing increase in canopy and growth of this vegetation.

The variation in reflectance among individual fires of the same age is also caused by events that preferentially affect certain areas, even within an ecoregion. An example is a period of high winds that can locally cause blowdown of fire-killed trees, changing the spectral signature and, in some cases, altering vegetation succession. Insect and disease impacts are also variable. Hence, much of the within-fire and among-fire variability is real and cannot be easily reduced by improving our detection.

Applications

The SWIR/NIR reflectance data clearly show recent fire scars on the landscape (Fig. 2). These data can be used as a tool to quickly delineate large fires, especially if they occurred within the previous decade or so. In practice, we have found fires that had not been in our original database. These were confirmed independently during more recent updates of the databases by the agencies. Hence, the SPOT-VGT data can be used for additional quality control of the large-fire database and to identify inconsistencies on the landscape. In some areas, fire polygons may be incorrectly plotted, and the SPOT-VGT data can clearly identify areas that need to be validated. However, the remotely sensed data cannot replace the in-depth fire reports and fire mapping that are routinely done by the agencies. If additional fires appear to be present on the landscape through the SPOT-VGT analysis, ground-truthing is required to verify that a fire has indeed occurred. This is because areas without vegetation for reasons other than fire can also show up as a false fire scar. In addition, the large pixel size (nominally about 1 km^2) is of poorer resolution than most aerial photography or global positioning system tracing methods that are currently used to map fires. The greatest applicability is largely in parts of northern Canada (Eastwood et al. 1998) where some agencies have not mapped all fires or perhaps in Siberia where this resource may be a welcome aid in fire mapping (e.g., Stocks et al. 1996). Fraser and Li (2002) found that their SPOT-VGT analysis underestimated the national area burned by 15% in 1998 and overestimated it by 11% in 1999 compared with Canadian statistics. This comparison suggests that their technique could be useful in estimating area burned within about 15% for large areas where fires are not mapped using conventional means.

Our ability to use the SPOT-VGT data to correctly estimate fire-scar age decreases with time since fire. In about half of the ecoregions, this is limited to about one decade following fire (Table 1). Here, the greatest success will be for dating fairly recent fires. However, the relationships are stronger in some ecoregions, even at 20 years or more. The 1998 SPOT-VGT data have the capability to get reasonable ages of polygons back into the 1970s in some areas. It is rare that fire polygons of an unknown year are mapped into

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the Canadian database, especially for more recent fires. Hence, there may be limited practical applications of using these algorithms for the existing database. However, fires that are mapped using SPOT-VGT can also be aged reliably, i.e., if the fire scar is clear, so is the age relationship. Fraser and Li (2002) used an artificial neural network to estimate fire-scar age for fires in Manitoba and Saskatchewan, with the best results having $r^2 = 0.7$ and RMS error of 7 years. Our ecoregion-based regressions have r^2 values similar to those of their neural network (Table 1). However, Fig. 5 shows that our RMS error increases from about 5 years within the first 5 years since fire to about 12 years at 30 years following fire. Such a large uncertainty does not allow the technique to be used for accurate dating, but it can give an estimate of approximate age.

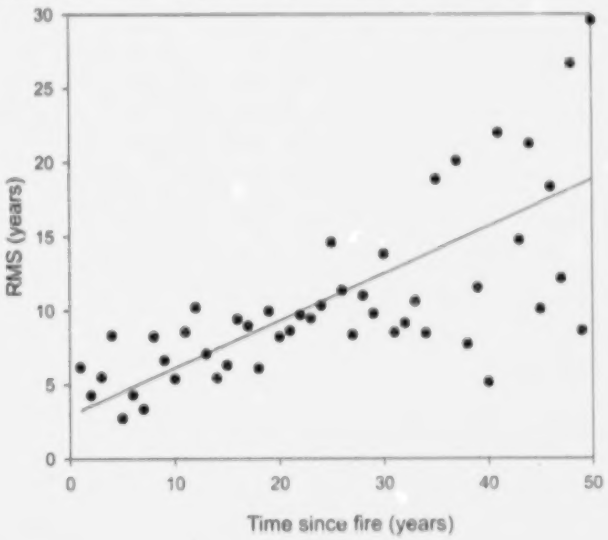
Presently, we have two forms of the large-fire database. The first is a point database, which includes attributes for each fire and the geographic point of fire origin (Stocks et al. 2002). The second is the fire polygon database, which shows the actual shape of the fire and coverage on the landscape. Considerable effort is being expended to ensure consistency between these two databases. However, the point database is more complete, and there is a need to delineate polygons for fires where polygon data are lacking. In many cases, this can be done by manually digitizing maps from fire reports that are archived. In some cases, a good fire map may not be available, especially in zones where fires are mostly observed and not aggressively suppressed (e.g., some parts of northwestern Ontario). The SPOT-VGT data allow polygons to be delineated quickly for large fires where the point of origin is known. The 1-km^2 pixel size is generally of sufficient resolution for the larger fires, especially those greater than 10 000 ha, where edge considerations are less important. For some agencies, delineating polygons has been replaced by plotting a circle that represents the size of the area burned, with the centre being the point of ignition. This circle gives an idea of the magnitude of fire on the landscape but cannot be used to determine where the burned area is located. For example, many large fires are driven by strong wind events, such that the point of origin is at the edge of the area burned. Hence, replacement of a circle with pixels generated from the SPOT-VGT analysis would be a great improvement and would be fast and cost-effective.

Algorithms developed with SPOT-VGT data are expected to be directly applicable to other satellite sensors with similar spectral bands, such as the series of Landsat sensors and MODIS sensors onboard Terra (http://terra.nasa.gov/About/MODIS/about_modis.html) and Aqua (http://eos-pm.gsfc.nasa.gov/) satellites. Landsat sensors have an additional SWIR band, and MODIS sensors not only have more spectral bands (36) than SPOT-VGT, but also have higher spatial resolutions (250 m for NIR and 500 m for SWIR bands) than SPOT-VGT. Improved remote sensing techniques, therefore, have the potential to date fire scars and estimate burn severity. It would be of considerable interest to the climate and ecosystem communities if the historical Landsat data can be used to extend and augment fire polygon records.

Uncertainties

Our analysis assumed that the large-fire database polygons were correct. During the matching of the polygons with the SPOT-VGT data, we did observe some inconsistencies that we believe are caused by incorrect fire polygons. In most cases, the fire polygon appeared to not cover exactly the correct fire location, as expressed by the SWIR/NIR values. However, this occurred rarely, and we do not believe that it had a large influence on the development of the relationship between fire-scar age and SWIR/NIR value. There also may be a small number of polygons that were incorrectly aged, but this is likely much smaller than 1%. We did not use any fires that were overlapped by any portion of another fire during the analysis period, but it is unlikely that this biased the analysis except for excluding older fires. The large pixel size of the SPOT-VGT data caused some edge complications. During the analysis, we converted the polygon vector data to a raster (gridded) format of the same pixel size as the SPOT-VGT data. This allowed the two data sets to be matched, but created averaging uncertainties at the edges of the fire. This could lower the mean SWIR/NIR values because (1) areas outside of the fire bounds have a lower ratio, (2) edges may have experienced lower fire severity, and (3) vegetation succession may be different at edges compared with the centre of the fire. We tested this effect using 460 fire polygons in ecoregion 88, where we compared reflectance from edge pixels (i.e., the first 1 km inside the fire boundary) with that from the full fire polygon. A paired t test (SPSS, Inc. 1997) of reflectance based on normalized pixel counts (13 015 edge pixels; 31 008 pixels in the full polygon) showed no significance difference ($P = 1.00$). Reflectance could also decrease because of unburned islands within the polygons, but this is likely less than 5% of the burned area (Eberhart and Woodward 1987; Kafka et al. 2001). In addition, fire severity varies within and among burned areas. Our large population of data includes this wide range, but the mean values in the regressions for any given

Fig. 5. Root mean square (RMS) difference between regressions shown in Table 1 and Fig. 4 and the data. RMS values were calculated for each year for all ecoregions ($n = 18$). Excluding one outlier point, the regression is $y = 0.32x + 2.9$, $r^2 = 0.50$.



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year smooth out this variation. Overall, we believe that our analysis provides a wide sample of fire severities.

Conclusions

Our comparison of SWIR/NIR ratio reflectance from SPOT-VGT with independent fire polygon data indicates that remote sensing can be used to identify and age recent fire scars. This has also been supported by Fraser and Li (2002). However, the change in reflectance over time is determined by vegetation succession following fire, which is highly variable on the landscape. Some of this variability can be reduced by developing separate relationships for each ecoregion, although we also find that some ecoregion groupings are appropriate. The nonlinear regressions between SWIR/NIR reflectance ratio and time since fire are strong, with most of them explaining two-thirds of the variability. However, about half of the ecoregions show only weak relationships for fire-scar ages older than one decade.

The SPOT-VGT data also show promise for mapping fire polygons, especially for large recent fires. This could save substantial effort for some agencies in busy fire years. It forms a good complement to the point database where a fire was known to occur. It can also be used for quality control of existing databases, although most of the conventionally mapped fire polygons have much greater detail than is possible with SPOT-VGT. A national map of the reflectances is also useful for many large-scale modelling activities, although ground-truthing is required if fire maps are developed as a product. Mapping of false positive polygons can be a problem, usually in areas of poor vegetation growth that look like recent fires, even though they are caused by insect infestations, disease, poor soils, or high water tables. Presently, only approximate fire-scar ages can be determined, and it is unlikely that this tool can replace the detailed fire mapping that is done currently by fire management agencies. On the other hand, this approximate dating technique can be applied to archived remote sensing images, such as the Landsat images since 1972, to extend fire polygon records for areas where such data are lacking. Additional comparisons are needed before the techniques can be applied to other landscapes, such as Siberia, where detailed fire maps may not be readily available.

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